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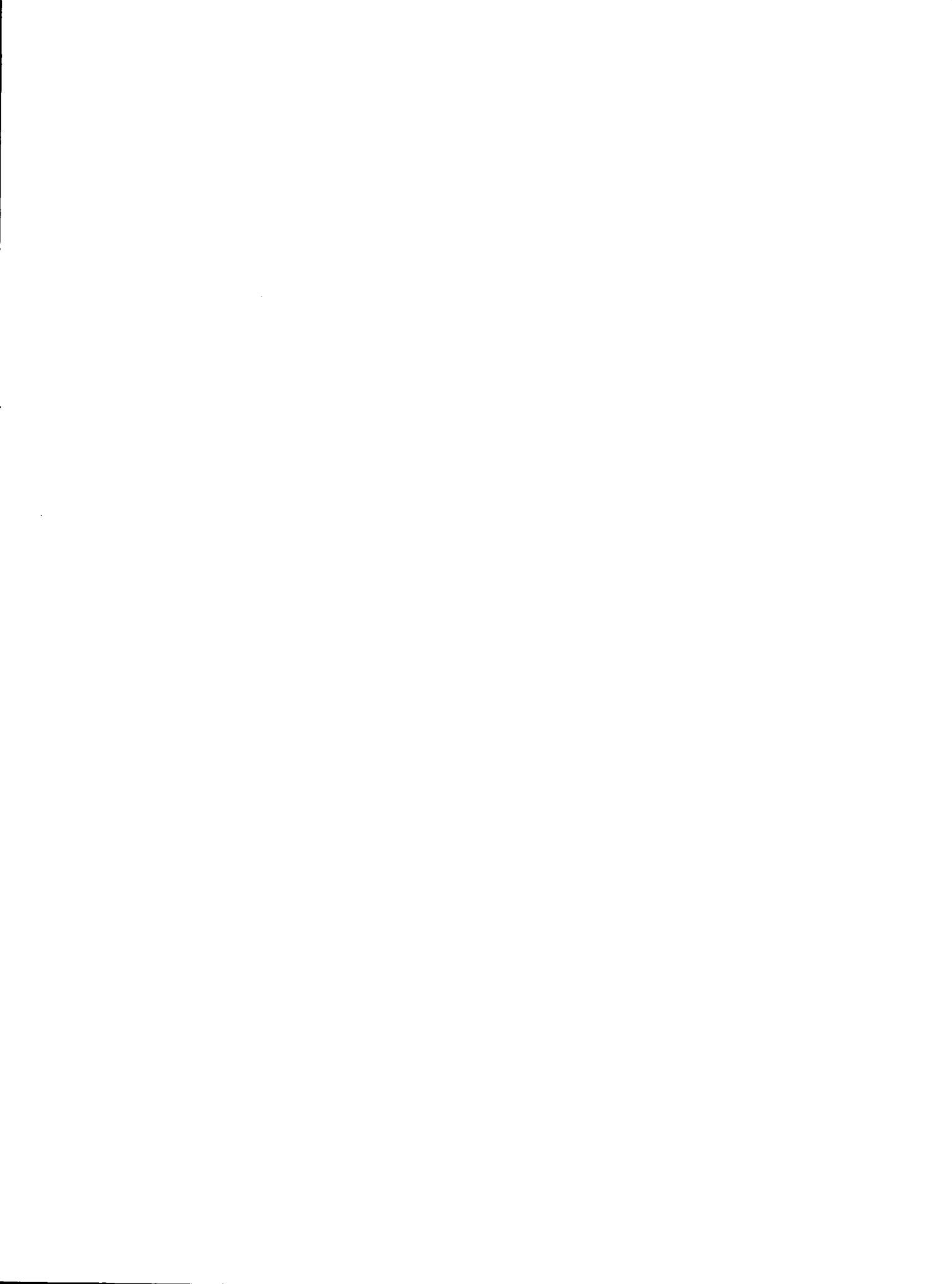
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New Technique for Calibrating Hydrocarbon Gas Flowmeters

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SUMMARY

A new technique has been developed for calibrating flowmeters for hydrocarbon gases. It is based on equalizing oxygen mole fraction in the combustion products of the test hydrocarbon, burnt in oxygen-enriched air, with that in the normal air. The technique has been tested for thermal mass flowmeters for several hydrocarbons and found to provide results in good agreement with those obtained by other independent procedures. It has been successfully applied to measure noncombustible contaminant concentrations in methane gas. Using this technique, differences in hydrocarbon content as low as 1 percent of the natural gas have been measured.

INTRODUCTION

Gas flowmeters are widely used in various scientific and industrial applications. Their efficient use requires frequent calibrations. Such routine calibrations are generally easy - except when the gases involved are rare, toxic, or highly reactive. Most of the hydrocarbons, however, fall in the latter category. A brief summary of fluid flowmeters is given in the appendix.

Normally, the flowmeters used for hydrocarbons are calibrated for air and require a special calibration factor for each hydrocarbon, depending on the physical principle involved in the operation of the flowmeter. These calibration correction factors have to be determined experimentally, since their calculation requires accurate knowledge about variation of essential gas parameters as a function of temperature and pressure. This information is not readily available for most of the hydrocarbons. It would be highly desirable if the flowmeter could be calibrated directly for the test hydrocarbon without first calibrating it for air or nitrogen. A new technique has been developed for direct on-line calibration of hydrocarbon flowmeters. Its underlying principle and experimental results obtained with several selected hydrocarbons are described in the following sections.

Of the various types of flowmeters discussed in the appendix, thermal mass flowmeters, based on the effect of the test medium flow on temperature distribution in a uniformly heated capillary tube, are the most widely used at Langley Research Center. As a result, these flowmeters were used for the present study. Like all other flowmeters, these units are normally calibrated for air and then used for other gases using conversion factors provided by the manufacturer. Theoretically, these conversion factors are given by the following expression (refs. 1 and 2):

$$G(\text{Test gas}) = \frac{C_p(\text{Air}) \text{ at standard temperature and pressure}}{C_p(\text{Test gas}) \text{ at standard temperature and pressure}} \tag{1}$$

However, experimentally determined values of G are not always in agreement with the calculated values, mainly because of the pressure and temperature gradients across the test capillary region. For this reason, it is always advisable to use experimentally determined values of G - particularly for high-accuracy measurements. This, however, is not always feasible with the conventional calibration procedures,

particularly when the gases are toxic or rare. Hydrocarbons, which are widely used in aeronautical and/or combustion kinetics laboratories, fall in the group of gases for which calibration is not routinely performed. As indicated previously, more often than not, one has to contend with the calculated values of the gas conversion factors which suffer from inherent inaccuracies.

SYMBOLS

A	mathematical constant
A_f	cross-sectional area of float
A_o	area of orifice
A_{th}	throat area
C_p	specific heat at constant pressure
$C(P)$	cell constant, determined by calibration with known gas mixtures at known pressures
C_xH_y	hydrocarbon molecule containing x atoms of carbon and y atoms of hydrogen
C'	rotameter correction factor for test fluid
d	capillary diameter
E	voltage output
FS	full scale
f	frequency of generated voltage signal
$f(PV)$	function of product of pressure and velocity of test medium to be determined by calibration procedure
G	gas flowmeter conversion factor
g	gravitational acceleration
$\dot{H}$	rate of heat loss to stream
H_t	heat supplied to heated tube
K	calibration constant
L	capillary length
ℓ	air flowrate
m	oxygen flowrate

n	hydrocarbon flowrate
p	flowrate of noncombustible additive gas
P	average gas pressure during measurement interval
P_t	total pressure ahead of restriction
P_1	partial pressure of oxygen in reference gas
P_2	partial pressure of oxygen in test gas
$\dot{Q}$	volumetric flowrate of fluid
STP	standard temperature and pressure
T	temperature
T_i	gas inlet temperature
T_o	gas outlet temperature
T_t	total temperature ahead of restriction
VARIAC	variable AC voltage source
v_f	volume of float
$X(O_2)$	mole fraction of oxygen
α	m/n when mole fraction of oxygen in output channel is same as in air
ΔP_c	pressure difference across capillary tube
ΔP_r	pressure difference across restriction
ΔT	mean temperature elevation of body above that of free stream
Δt	time difference between reception of two oppositely directed sound pulses
μ	absolute viscosity
ρ	density of test fluid
ρ_f	density of float material

OPERATING PRINCIPLE

A fast system was recently developed for monitoring and controlling the oxygen concentration in (CH_4-O_2-Air) combustion product gases in the NASA Langley 8-Foot High Temperature Tunnel. (See ref. 3.) The oxygen sensor is a Y_2O_3-stabilized ZrO_2 ceramic disc maintained at a high temperature. (See refs. 4 and 5.) Its voltage

output E varies with the oxygen partial pressure on its two sides, according to the following relation (ref. 6):

$$E = AT \ln\left(\frac{P_1}{P_2}\right) + C(P)$$

(2)

where

A   mathematical constant

T   temperature of ZrO_2 disc

P_1 partial pressure of oxygen in reference gas

P_2 partial pressure of oxygen in test gas

C(P)   cell constant (determined by calibration with known gas mixtures at known pressures)

During the development phase of the system, it became obvious that the oxygen monitoring technique could also be adapted for direct measurement of conversion factors for all hydrocarbon gas flowmeters. (See ref. 7.)

The essential chemistry of the hydrocarbon combustion process in oxygen-enriched air is represented by the following equation:

$$\ell(\text{Air}) + m(O_2) + n(C_xH_y) \longrightarrow \ell(\text{Air}) + nx(CO_2) + \frac{n}{2} y(H_2O) + \left[m - n\left(\frac{4x + y}{4}\right)\right](O_2) + \text{Heat}$$
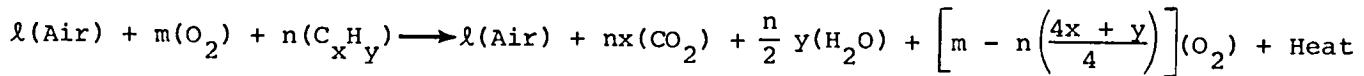
     <u>Input channel</u>   <u>Output channel</u>

(3)

This equation assumes that the added oxygen in the input channel was equal to the amount needed for complete combustion of the hydrocarbon. The mole fraction of oxygen in the output channel of equation (3) is given by the following equation:

$$X_2(O_2) = \frac{0.2095\ell + \left[m - n\left(\frac{4x + y}{4}\right)\right]}{\ell + nx + \frac{n}{2} y + \left[m - n\left(\frac{4x + y}{4}\right)\right]}$$

(4)

If the mole fraction of oxygen in the output channel is the same as in the reference gas (air), then

$$0.2095 = \frac{0.2095\ell + \left[m - n\left(\frac{4x + y}{4}\right)\right]}{\ell + nx + \frac{n}{2} y + \left[m - n\left(\frac{4x + y}{4}\right)\right]}$$

(5)

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Simplifying equation (5) yields

$$\frac{m}{n} = \frac{4x + 1.2095y}{4(1 - 0.2095)} = \alpha \qquad (6)$$

For the special case of $C_xH_y = CH_4$, equation (6) simplifies as follows:

$$\alpha = 2.795 \qquad (7)$$

Calculated values of α for other hydrocarbons are listed in table I. It is apparent from equation (6) that α is independent of the value of ℓ, though the latter does determine the sustainability of the hydrocarbon flame. The optimum value of ℓ ranges from 2 m to 3 m. (See ref. 3.)

The condition specified by equation (5) is signaled by the production of the same oxygen sensor output as is obtained with air as the test gas. The relationship between oxygen and hydrocarbon concentrations given by equation (6) can be used as the basis for hydrocarbon flowrate calculation if the oxygen flowrate is known. Oxygen conversion factors are usually supplied by the thermal mass flowmeter manufacturers because of widespread use of oxygen in chemistry and combustion laboratories.

EXPERIMENTAL PROCEDURE

Figure 1 is a schematic of the experimental system used for equalizing partial pressures of oxygen in the test gas and the reference air. Typically, the hydrocarbon under test is burnt in oxygen-enriched air in a well-stirred combustor to ensure complete combustion. A fraction of the combustion products is passed through the oxygen partial pressure monitor. For a particular dial setting of the hydrocarbon flowmeter, the oxygen flowrate is adjusted to make the oxygen partial pressure in the combustion products the same as in the reference air. This condition is signaled by the production of the same cell output as is obtained when normal air is used as the test gas. The hydrocarbon flowmeter conversion factor G is then given by the equation

$$
\begin{aligned}
G &= \frac{O_2 \text{ flowrate}}{(\alpha)_{\text{Hydrocarbon}} (\text{Hydrocarbon flowrate on dial})} \\[2ex]
&= \frac{O_2 \text{ flowrate}}{2.795(CH_4 \text{ flowrate on dial})} \qquad (\text{For methane gas}) \\[2ex]
&= \frac{O_2 \text{ flowrate}}{3.295(C_2H_2 \text{ flowrate on dial})} \qquad (\text{For acetylene gas})
\end{aligned} \qquad (8)
$$

This method is applied to thermal mass flowmeters used widely in chemical and aerospace laboratories. However, in principle, the procedure is applicable to all other mass flowmeters, regardless of their operating principles.

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RESULTS

Typical results obtained with selected hydrocarbons are summarized in tables II and III. The last column of each of these tables lists the values of the calculated conversion factors (ref. 8) for the test gases at standard temperature and pressure during their transport through the heated element of the flowmeter. However, the temperature and pressure of the test gases through the heated element are not standard, and their values are not easily measured. This makes the calculated conversion factor values suspect and requires their experimental determination for all hydrocarbons and other gases whose values of C_p vary significantly with temperature and pressure.

As is evident from equation (6), α is independent of ℓ and n. To test this hypothesis, detailed repeat measurements were made for methane and acetylene gases for several combinations of air and oxygen flowrates. These results are summarized in tables IV and V and illustrated in figures 2 to 5. It is apparent that the CH_4 and C_2H_2 conversion factors are independent of the oxygen flowrates and the carrier-gas (air) flowrates.

FURTHER TESTS

As an extension of the present study, it was decided to test the validity of the operating principle of the new technique by using ($CH_4 + N_2$) and ($CH_4 + CO_2$) mixtures as the test gases. Since N_2 and CO_2 are not combustible, their only effect is on the mole fraction of O_2 in the exhaust channel. Figure 6 is a schematic of the experimental system used for these tests. Based on the experimentally measured values of O_2 partial pressures, the additive-gas flowrates have been calculated and compared with their independently measured values. The data are summarized in table VI. The flowrates for the CH_4 gas are averages of several measurements for a given combination of ℓ, m, and p flowrates. The errors listed are indicative of spread among individual values and were obtained by the method of least squares. The agreement between the measured and calculated flowrates for the additive gases is good, thereby confirming the validity of the new technique.

As a test of the reliability of the new technique for monitoring the quality (i.e., hydrocarbon content) of a test gas, gas samples were collected from the natural gas pipeline at Langley Research Center before and after passing through a gas compressor. Figure 7 shows the experimental setup used for monitoring the effect of compression on the quality of the natural gas. The hydrocarbon contents of these samples were compared with those of commercial methane gas. The results are summarized in table VII. The flowrates for CH_4, natural gas before compression (NG(B)), and natural gas after compression (NG(A)) listed in columns 3 to 5 are averages of several measurements for a given combination of air and oxygen flowrates. The errors listed were obtained by the method of least squares. It is obvious that the effective hydrocarbon content of the natural gas samples is lower than that of the commercial methane gas. Furthermore, the hydrocarbon content of NG(A) is slightly higher than that of NG(B). To further verify this conclusion, the two natural-gas samples were analyzed by a gas chromatograph. The results are summarized in table VIII. The effective hydrocarbon content of the NG(A) sample is slightly higher than that of the

NG(B) sample.[1] Therefore, it appears that the new technique has a distinct potential for monitoring the quality of the test gas.

DISCUSSION

The new technique for calibrating flowmeters for hydrocarbon gases is attractive for the following reasons:

1. It is based on very low flowrates, thus causing minimum loss of rare gas samples.

2. It is self-regulating, thus minimizing the risk of the release of unburnt toxic species into the laboratory environment.

3. It is independent of the operating principle of the flowmeter; that is, it provides an independent measure of the true flowrates of the hydrocarbons under study.

4. It lends itself to easy and convenient incorporation into standard laboratory calibration procedures.

5. It has the potential of providing information about the noncombustible impurities that might be present in the test stream.

The technique has been used to calibrate thermal mass flowmeters, widely used in this laboratory, for a number of hydrocarbons. In most instances, the calculated values of the calibration constants differ from the experimental values, mainly because C_p values for most hydrocarbons vary significantly with temperature and pressure. In those instances where directly measured "empirical" values of the calibration factors are available, the present values are in reasonable agreement with them.

The technique has also been tested to obtain information about the noncombustible components in the test-gas stream. Two inert gases, N_2 and CO_2, were introduced in the CH_4 stream at measured rates, and their concentrations were inferred on the basis of the newly developed calibration procedure. The measured values of the N_2 and CO_2 contaminants were in good agreement with the inferred values. This capability was later exploited to determine if the quality of the natural gas changes as it goes through a 6-kpsi compressor into the storage cylinder. It was speculated that some of the stream components might condense out, thus changing the pipe-gas composition. Results summarized in table VII indicate that the effective hydrocarbon contents of samples NG(A) and NG(B) are in the ratio 1.000:(0.990 ± 0.002). According to the gas chromatographic data summarized in table VIII, the effective hydrocarbon contents of samples NG(A) and NG(B) are in the ratio 1.000:(0.994 ± 0.001). The slight difference between these two values may be due to trace condensables – such as

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[1]The compressor was operated in six stages, from 50 psi to a final pressure of 6 kpsi, with equal pressure ratio across each stage. The gas temperature was reduced to ambient after each stage. Under these conditions, some of the heavier hydrocarbons present in the natural gas may condense. This may be expected to reduce the effective hydrocarbon content of the pipe gas. However, simultaneous removal of the noncombustible components – such as H_2O and CO_2 – may lead to an overall increase in the effective hydrocarbon content.

H_2O - not detected with the gas chromatograph. From these data, it is apparent that the effective hydrocarbon content of the gas after going through the compressor is slightly higher than that before compression.

CONCLUDING REMARKS

A new technique has been developed for calibrating flowmeters for hydrocarbon gases. It is based on oxygen partial-pressure measurement in products of combustion of the test hydrocarbon gas in oxygen-enriched air. The new technique has the potential to provide information about the concentration of the noncombustible contaminants that may be present in the test-gas stream. Also, the new technique can serve as the basis for a real-time monitor for the quality of natural gas used in aeronautical and industrial laboratories and can permit detection of differences as low as 1 percent in the hydrocarbon content of the test gases.

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APPENDIX

SUMMARY OF FLUID FLOWMETERS

There are many types of flowmeters currently in use. Some are described in this appendix.

Turbine Flowmeters

These flowmeters are velocity-sensing devices whose signal output frequency varies directly with the actual fluid flowrates. (See ref. 9.) They are character-ized by a calibration correction factor K defined as follows:

$$K = \frac{f}{\dot{Q}} \tag{A1}$$

where

f   frequency of generated voltage signal

$\dot{Q}$ volumetric flowrate of the fluid

Clearly, K has to be measured for each test gas.

Variable-Area Flowmeters (Rotameters)

In these instruments, the flowing fluid raises a float in a tapered tube so as to increase the annular area of the fluid column. (See refs. 10 and 11.) The greater the flowrate, the higher the float is raised. The float height is thus proportional to the fluid flowrates. It is necessary to recalibrate the rotameter gas units frequently because of the interdependence of density, pressure, and tem-perature. Nearly all the units are provided with factory calibration for air at standard temperature and pressure and for water at a specific gravity of 1. Recon-structing calibration curves for other fluids is simple and direct, in principle, with the use of correction equations of the following form (ref. 12):

$$\dot{Q} = C' \sqrt{\frac{2g v_f (\rho_f - \rho)}{\rho A_f}} \tag{A2}$$

where

v_f volume of float

A_f cross-sectional area of float

ρ_f density of float material in weight units

ρ density of test fluid in weight units

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C'   rotameter correction factor for test fluid (including effects of drag coefficient of float in test fluid)

g   gravitational acceleration (1g = 9.8 m/s^2)

Head-Type Flowmeters

These flowmeters include orifice meters, Venturi tubes, critical flowmeters or nozzles, and laminar-flow tubes. In these instruments, the flowrate is inferred from the pressure difference measured across a restriction in the flow stream. For the orifice and Venturi flowmeters, the flowrate is given by an equation of the following form:

$$\dot{Q} = A_o K \sqrt{2g \frac{\Delta P_r}{\rho}} \qquad (A3)$$

where

A_o area of orifice

K   calibration constant

ΔP_r pressure difference across restriction

ρ density of test fluid in weight units

These flowmeters are sensitive to Reynolds number, velocity, and compressibility effects and require accurate calibration for each gas. For critical flowmeters, the flow equation takes the following form:

$$\dot{Q} = \frac{KA_{th}}{\rho} \frac{P_t}{\sqrt{T_t}} \qquad (A4)$$

where

K   calibration constant

A_{th} throat area

P_t total pressure ahead of restriction

T_t total temperature ahead of restriction

The laminar-flow tubes operate at low Reynolds numbers ($<1.0 \times 10^3$) where fluid viscosity causes the differential pressure to vary linearly with the flowrate. The flowrate for these flowmeters is given by the following equation:

$$\dot{Q} = K \frac{\Delta P_c \pi d^4}{128 \mu L} \qquad (A5)$$

where

K   calibration constant

ΔP_c pressure difference across capillary tube

d   capillary diameter

L   capillary length

μ absolute viscosity

Except for choked flowmeters, whose calibration constant can be calculated accurately if the gas properties are fully known, all other differential-pressure flowmeters require accurate, experimentally determined calibration correction factors for various gases.

Ultrasonic Mass Flowmeters

These instruments are based on differences in transit times of two oppositely directed ultrasound waves between two piezoelectric microphones located in the stream at a fixed distance apart. Once a flow has been fully established, an equation of the following form can be used to provide information about the gas flowrate (ref. 13):

$$\dot{Q} = \frac{KP}{\rho} \Delta t \tag{A6}$$

where

K   calibration constant

P   average gas pressure during measurement interval

Δt time difference between reception of two oppositely directed sound pulses

ρ density of test fluid in mass units

The constant K is a function of the gas properties and needs to be determined for each gas. (At low velocities where laminar flow occurs, K does not remain constant because of steep spatially variable velocity profiles.)

Thermal Flowmeters

These instruments depend upon the exchange of heat between the test fluid and a hot body in the flow stream. There are two types of thermal flowmeters. The first type is based on the effect of the test-medium flow on the temperature distribution in a uniformly heated capillary tube. (See refs. 1 and 2.) The temperature distribution is symmetrical about the capillary midpoint at zero flow. When a flow occurs through the tubing, an asymmetrical temperature distribution occurs. The

differential thermocouple output across the capillary section is related to the thermal capacity and flowrate of the test gas according to the following equation:

$$\dot{Q} = \frac{1}{\rho}\left[\frac{H_t}{C_p(T_o - T_i)}\right] \tag{A7}$$

where

H_t heat supplied to heated tube

C_p specific heat of test gas at constant pressure

T_o gas outlet temperature

T_i gas inlet temperature

ρ density of test fluid in mass units

These flowmeters indicate mass flowrates with a reasonably high accuracy (< 2 percent of full scale) over a wide range without requiring corrections for pressure or temperature variations. They are useful from the very low flowrates in high-vacuum systems to the large flowrates in natural-gas pipes. The second type of flowmeter is based on the effect of the flow stream on the body immersed in it. In one commonly used variety (ref. 14), the correlation of the gas velocity is made with the hot-body resistance change. The general equation for a hot-wire anemometer is of the following form:

$$\dot{H} = \Delta T \ f(PV) \tag{A8}$$

where

$\dot{H}$ rate of heat loss to stream

ΔT mean temperature elevation of body above that of free stream

$f(PV)$ function of product of pressure and velocity of test medium to be determined by calibration procedure

These hot-wire instruments require frequent calibration, because the sensing elements become coated with the stream impurities. They are of limited usefulness because of the need for different correction factors for different flow conditions.

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TABLE I.- SUMMARY OF CALCULATED VALUES OF α FOR SELECTED
UNBRANCHED ACYCLIC HYDROCARBONS

Hydrocarbon	Chemical formula (C_xH_y)	α
Methane	CH_4	2.795
Ethane	C_2H_6	4.825
Propane	C_3H_8	6.855
Butane	C_4H_{10}	8.885
Pentane	C_5H_{12}	10.915
Hexane	C_6H_{14}	12.945
Heptane	C_7H_{16}	14.975
Octane	C_8H_{18}	17.005
Nonane	C_9H_{20}	19.035
Decane	$C_{10}H_{22}$	21.065
Acetylene	C_2H_2	3.295

TABLE II.- SUMMARY OF CONVERSION-FACTOR MEASUREMENTS FOR SELECTED SATURATED HYDROCARBONS

$$\left[\begin{array}{c}\text{The errors on the experimental conversion factors include the effects of errors} \\ \text{associated with Air, } O_2, \text{ and } C_xH_y \text{ flowmeters (}\pm 1 \text{ percent FS)}\end{array}\right]$$

Air flowrate, ℓ, cm^3/min	O_2 flowrate, m, cm^3/min	Hydrocarbon flowrate, cm^3/min (dial reading)	Sampled flowrate, cm^3/min (air equivalent)	Gas conversion factor, G (experimental)	Gas conversion factor, G (calculated)[a]
		Methane (CH$_4$)			
1400	391.1	200	1300	0.701	0.815
1400	427.8	220	1300	.699	
1400	469.0	240	1300	.696	.69[b]
				0.699 ± 0.020	
		Ethane (C$_2$H$_6$)			
1700	679.0	307	2000	0.458	0.56
1700	727.5	329/330	2000	.458	
1700	776.0	351	2000	.458	
1700	824.5	372	2000	.459	
1700	873.0	392/393	2000	.461	
				0.459 ± 0.020	
		Propane (C$_3$H$_8$)			
1700	679.0	312	2000	0.317	0.394
1700	727.5	334	2000	.318	
1700	776.0	356	2000	.318	.32[b]
1700	824.5	377	2000	.320	
				0.318 ± 0.020	
		Butane (C$_4$H$_{10}$)			
1700	679.0	303/304	2000	0.252	0.30
1700	727.5	324	2000	.253	
1700	776.0	346	2000	.252	
1700	824.5	365	2000	.254	
				0.253 ± 0.020	

[a]The calculated value is given by

$$G = \frac{C_p(\text{Air}) \text{ at STP}}{C_p(\text{Test gas}) \text{ at STP}}$$

[b]The empirical values have been taken from reference 15. Apparently, they are experimental values determined by the manufacturer.

TABLE III.- SUMMARY OF CONVERSION-FACTOR MEASUREMENTS FOR ACETYLENE (C_2H_2)

[The error on the experimental conversion factor includes the effects of errors associated with Air, O_2, and C_2H_2 flowmeters (±1 percent FS)]

Air flowrate, ℓ, cm^3/min	O_2 flowrate, m, cm^3/min	Acetylene flowrate, cm^3/min (dial reading)	Sampled flowrate, cm^3/min (air equivalent)	Gas conversion factor, G (experimental)	Gas conversion factor, G (calculated)[a]
1400	426.8	200	1300	0.648	0.656
1400	471.4	220	1300	.650	
1400	508.3	240	1300	.643	.67[b]
				0.647 ± 0.020	

[a]The calculated value is given by

$$G = \frac{C_p \text{(Air) at STP}}{C_p \text{(Test gas) at STP}}$$

[b]The empirical value has been taken from reference 15. Apparently, it is the experimental value determined by the manufacturer.

TABLE IV.- SUMMARY OF RESULTS FOR METHANE FLOWMETER CONVERSION FACTOR
FOR SEVERAL COMBINATIONS OF AIR AND OXYGEN FLOWRATES

Air flowrate, ℓ, cm^3/min (true reading)	O_2 flowrate, m, cm^3/min (true reading)	CH_4 flowrate, n, cm^3/min (dial reading)	Sampled flowrate, cm^3/min (air equivalent)	O_2 partial-pressure monitor output, mV	CH_4 conversion factor, G
1300	0	0	1300	-19.05 ± 0.05	
1000	391.9	200	1300	-19.05 ± 0.05	0.701
1000	426.8	220	1300	-19.05 ± 0.05	.694
1000	465.1	240	1300	-19.05 ± 0.05	.693
1200	391.9	200	1300	-19.05 ± 0.05	.701
1200	426.8	220	1300	-19.05 ± 0.05	.694
1200	467.5	240	1300	-19.05 ± 0.05	.697
1400	391.9	200	1300	-19.05 ± 0.05	.701
1400	427.8	220	1300	-19.05 ± 0.05	.699
1400	469.0	240	1300	-19.05 ± 0.05	.696
					0.697 ± 0.020[a]

[a]Including the effects of errors associated with the O_2 and CH_4 flowrate indications, the final value of the conversion factor is calculated to be 0.697 ± 0.020. This value should be compared with G = 0.69 listed by the flowmeter manufacturer (ref. 15).

TABLE V.- SUMMARY OF RESULTS FOR ACETYLENE FLOWMETER CONVERSION FACTOR
FOR SEVERAL COMBINATIONS OF AIR AND OXYGEN FLOWRATES

Air flowrate, ℓ, cm^3/min (true reading)	O_2 flowrate, m, cm^3/min (true reading)	C_2H_2 flowrate, n, cm^3/min (dial reading)	Sampled flowrate, cm^3/min (air equivalent)	O_2 partial-pressure monitor output, mV	C_2H_2 conversion factor, G
1300	0	0	1300	-19.05 ± 0.05	
1000	426.8	200	1300	-19.05 ± 0.05	0.648
1000	470.5	220	1300	-19.05 ± 0.05	.649
1000	508.3	240	1300	-19.05 ± 0.05	.643
1200	426.8	200	1300	-19.05 ± 0.05	.648
1200	470.5	220	1300	-19.05 ± 0.05	.649
1200	509.3	240	1300	-19.05 ± 0.05	.644
1400	426.8	200	1300	-19.05 ± 0.05	.648
1400	471.4	220	1300	-19.05 ± 0.05	.650
1400	508.3	240	1300	-19.05 ± 0.05	.643
					0.644 ± 0.020[a]

[a]Including the effects of errors associated with the O_2 and C_2H_2 flowrate indications, the final value of the conversion factor is calculated to be 0.644 ± 0.020. This value should be compared with G = 0.67 listed by the flowmeter manufacturer (ref. 15).

TABLE VI.- COMPARISON BETWEEN THE CALCULATED AND THE MEASURED VALUES OF "CONTAMINANT" GAS IN THE CH_4 STREAM

(a) $CH_4 + N_2$

Air flowrate,[a] ℓ, cm^3/min	O_2 flowrate,[b] m, cm^3/min	CH_4 flowrate,[c,d] n, cm^3/min	$CH_4 + N_2$ flowrate, n + p, cm^3/min	N_2 flowrate, p, cm^3/min	
				Measured[e]	Calculated[f]
1700	873.0	312.3 ± 0.4	312.3 ± 0.4	0	0
	873.0	310.9 ± 0.7	320.9 ± 0.7	10.0	9.5 ± 0.8
	873.0	310.9 ± 0.5	330.9 ± 0.5	20.0	20.5 ± 0.1
	873.0	310.2 ± 1.5	340.2 ± 1.5	30.0	30.8 ± 1.6
	873.0	308.8 ± 1.0	348.8 ± 1.0	40.0	40.3 ± 0.7
1700	824.5	295.0 ± 0.4	295.0 ± 0.4	0	0
	824.5	293.6 ± 0.2	303.6 ± 0.2	10.0	9.5 ± 0.6
	824.5	293.7 ± 0.2	313.7 ± 0.2	20.0	20.6 ± 0.1
	824.5	293.2 ± 0.9	323.2 ± 0.9	30.0	31.2 ± 1.0
	824.5	292.6 ± 0.5	332.6 ± 0.5	40.0	41.5 ± 0.5

[a]Measurement error is ±20 cm^3/min.
[b]Measurement error is ±10 cm^3/min.
[c]Measurement error is ±3.5 cm^3/min.
[d]These values were obtained by adjusting the CH_4 flowrates to make $X(O_2)$ for the combustion product channel the same as for normal air (i.e., 0.2095).
[e]Measurement error is ±1 cm^3/min.
[f]The N_2 concentration has been calculated on the basis of the following equation:

$$X(O_2) = \frac{0.2095\ell + (m - 2n)}{\ell + m + n + p} = \frac{356.15 + (m - 2n)}{1700 + (m + n + p)}$$

TABLE VI.- Concluded

(b) $CH_4 + CO_2$

Air flowrate,[a] ℓ, cm^3/min	O_2 flowrate,[b] m, cm^3/min	CH_4 flowrate,[c,d] n, cm^3/min	$CH_4 + CO_2$ flowrate, n + p, cm^3/min	CO_2 flowrate, p, cm^3/min	
				Measured[e]	Calculated[f]
1700	873.0	312.3 ± 0.4	312.3 ± 0.4	0	0
	873.0	310.9 ± 0.4	318.2 ± 0.4	7.3	6.5 ± 0.1
	873.0	310.2 ± 0.8	324.8 ± 0.8	14.6	14.8 ± 0.9
	873.0	310.9 ± 0.8	340.1 ± 0.8	29.2	29.7 ± 0.9
	873.0	308.1 ± 0.7	351.9 ± 0.7	43.8	44.5 ± 0.8
1700	824.5	295.0 ± 0.4	295.0 ± 0.4	0	0
	824.5	294.5 ± 0.7	301.8 ± 0.7	7.3	8.3 ± 0.6
	824.5	294.0 ± 1.0	308.6 ± 1.0	14.6	16.1 ± 1.5
	824.5	295.3 ± 1.2	324.5 ± 1.2	29.2	30.8 ± 1.6
	824.5	291.9 ± 0.8	335.7 ± 0.8	43.8	45.8 ± 1.1

[a]Measurement error is ±20 cm^3/min.
[b]Measurement error is ±10 cm^3/min.
[c]Measurement error is ±3.5 cm^3/min.
[d]These values were obtained by adjusting the CH_4 flowrates to make $X(O_2)$ for the combustion product channel the same as for normal air (i.e., 0.2095).
[e]Measurement error is ±0.7 cm^3/min.
[f]The CO_2 concentration has been calculated on the basis of the following equation:

$$X(O_2) = \frac{0.2095\ell + (m - 2n)}{\ell + m + n + p} = \frac{356.15 + (m - 2n)}{1700 + (m + n + p)}$$

TABLE VII.- SUMMARY OF RESULTS OF METHANE COMPARED WITH NATURAL GAS (AFTER
COMPRESSION) AND NATURAL GAS (BEFORE COMPRESSION) FOR AIR
EQUIVALENT-COMBUSTION PRODUCT CHANNEL

Air flowrate,[a] ℓ, cm^3/min	O_2 flowrate,[b] m, cm^3/min	CH_4 flowrate,[c,d] n, cm^3/min	Natural gas[c,d] before compression, NG(B), cm^3/min	Natural gas[c,d] after compression, NG(A), cm^3/min
1700	776.0	392.9 ± 0.5[e]	399.6 ± 0.8	395.9 ± 0.8
1700	824.5	414.7 ± 0.8	421.8 ± 1.2	418.0 ± 0.7
1700	873.0	436.1 ± 0.5	445.8 ± 0.8	440.1 ± 0.8

[a]Measurement error is ±20 cm^3/min.
[b]Measurement error is ±10 cm^3/min.
[c]Measurement error is ±3.5 cm^3/min.
[d]These flowrates have not been corrected for the gas composition. For CH_4, our calculated value of the meter correction factor is 0.697 ± 0.020.
[e]The methane content of the commercial gas was listed as 98 percent by the supplier.

TABLE VIII.- SUMMARY OF RESULTS OF GAS CHROMATOGRAPHIC ANALYSIS OF
NATURAL-GAS SAMPLES

Gas species	Natural gas before compression, NG(B), percent	Natural gas after compression,[a] NG(A), percent
CH_4	95.91	96.52 ± 0.20
C_2H_6	2.14	2.32 ± 0.08
C_3H_8	.37	0.40 ± 0.03
C_4H_{10}	.20	0.14 ± 0.02
C_5H_{12}	.10	<0.05
C_6H_{14}	.01	<<0.05
CO_2	.84	0.22 ± 0.02
N_2	.43	0.39 ± 0.06

[a]These values are averages of two independent measurements
of the same sample.
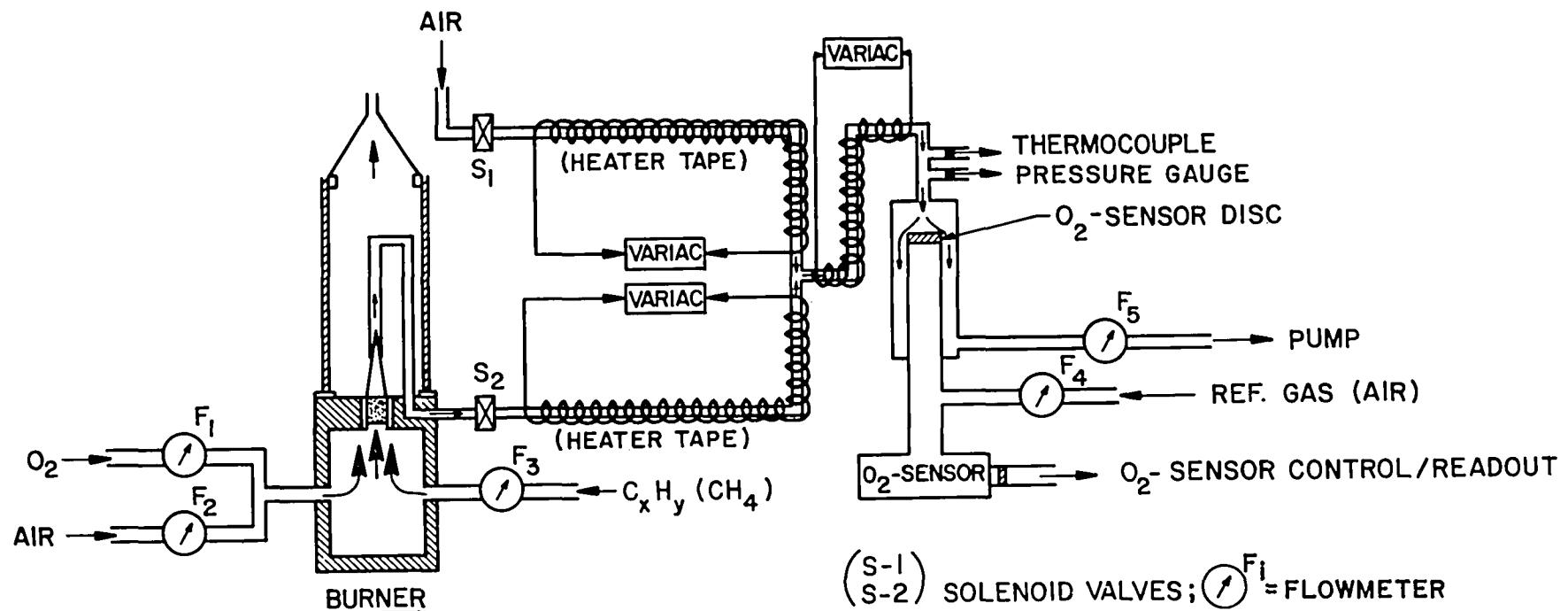
Figure 1.- Experimental system for measuring flowrates for hydrocarbon gases.
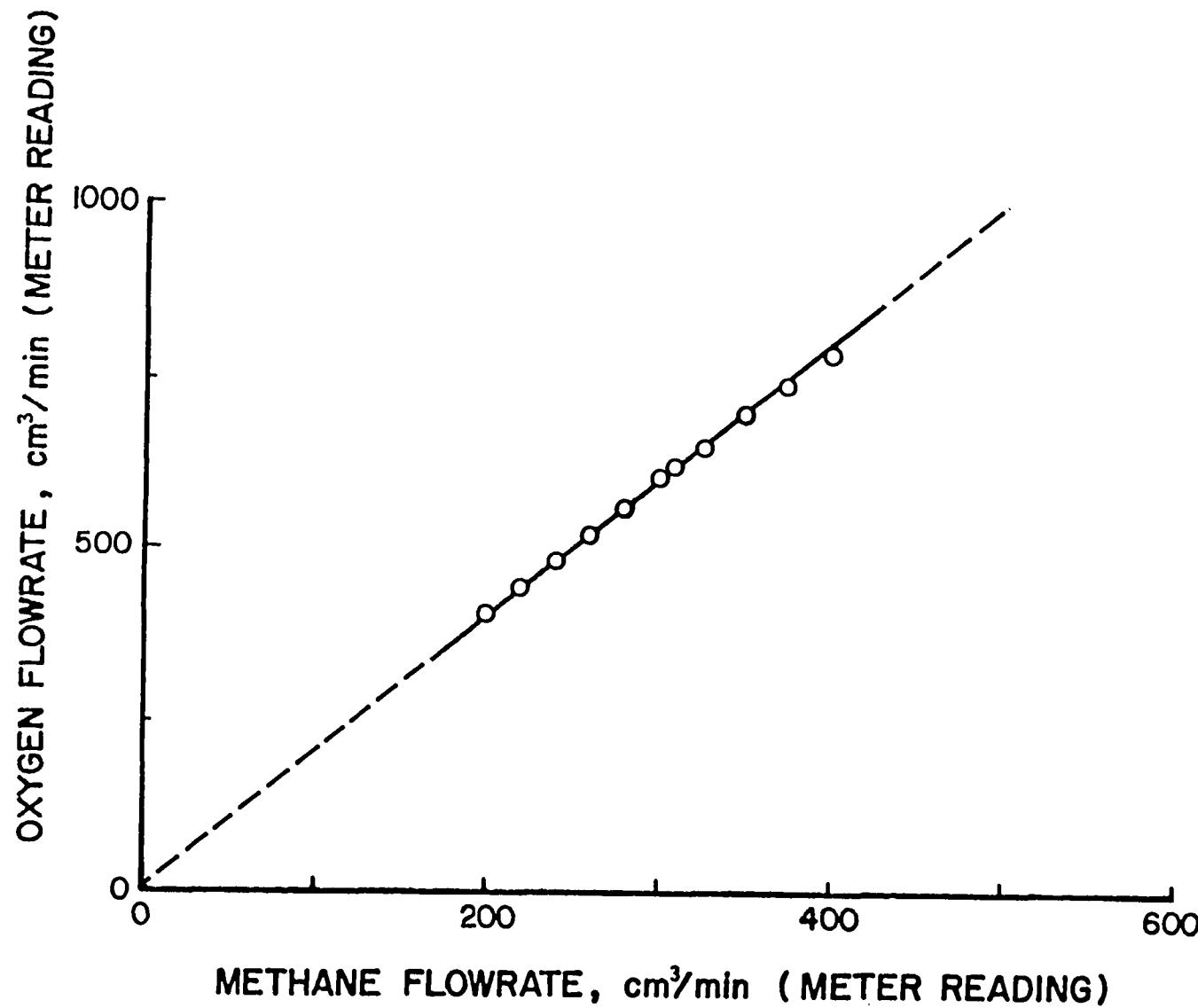
Figure 2.- Oxygen flowrate versus methane flowrate for making $X(O_2)$ in combustion products equal to that in normal air.
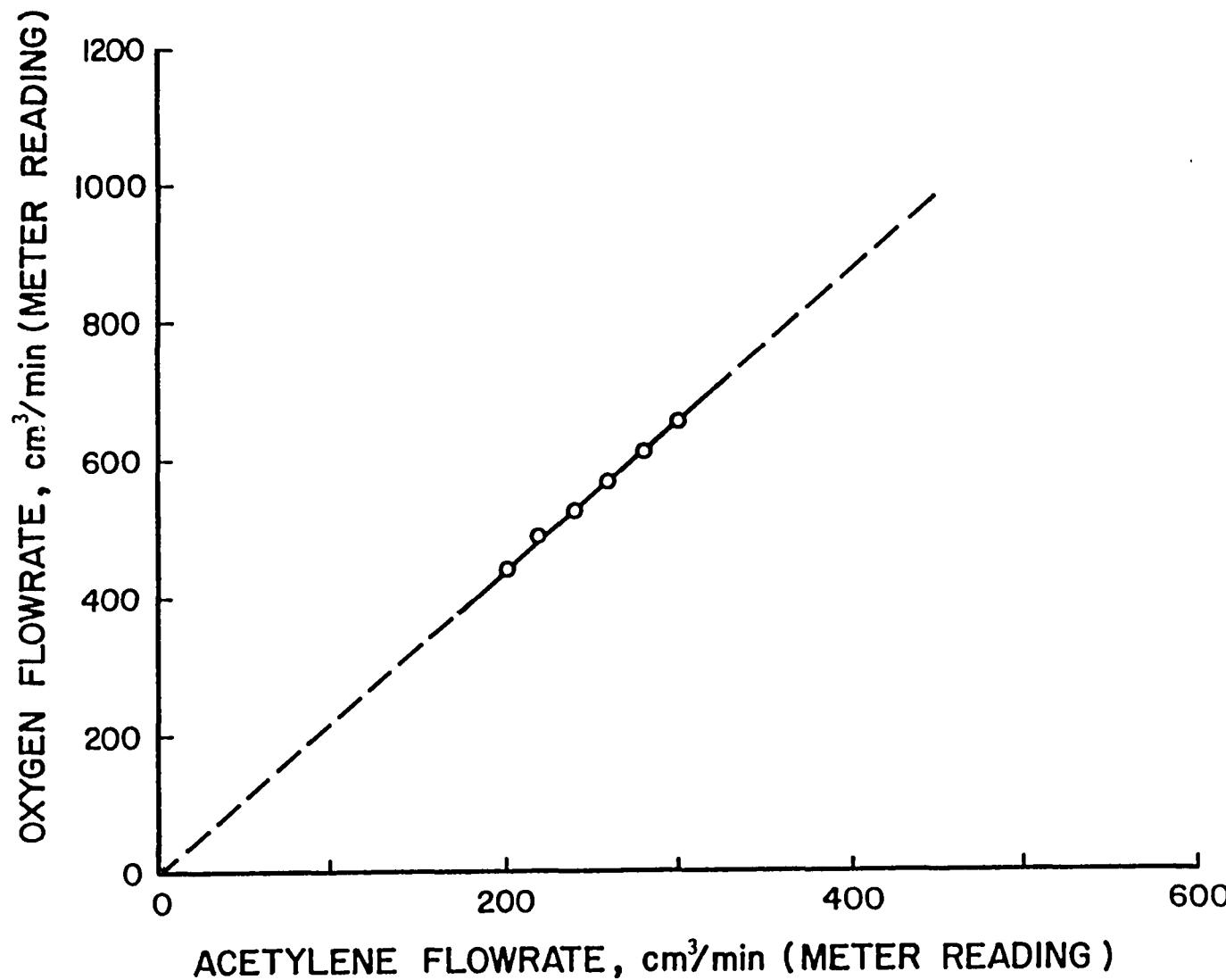
Figure 3.- Oxygen flowrate versus acetylene flowrate for making $X(O_2)$ in combustion products equal to that in normal air.
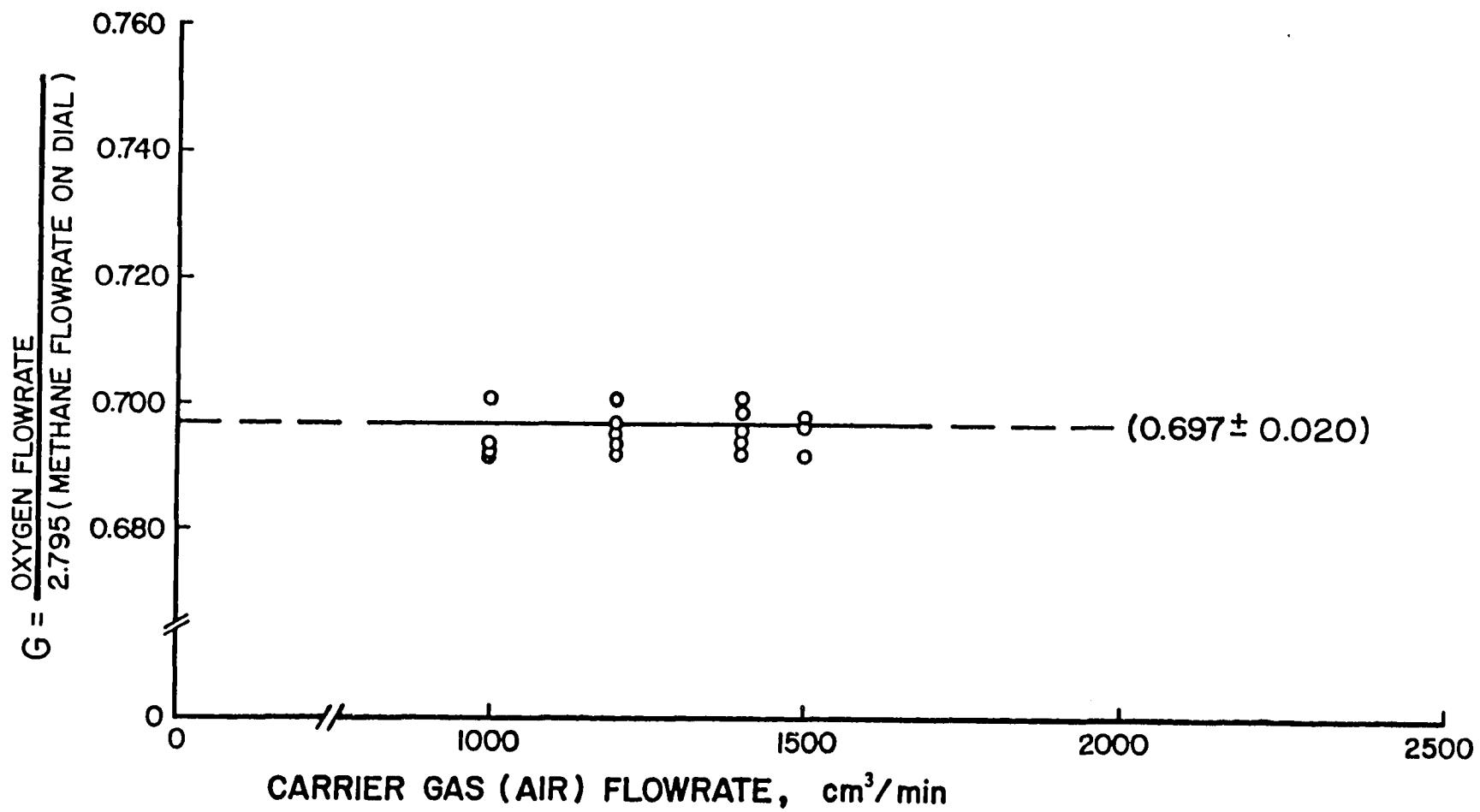
Figure 4.- Dependence of methane conversion factor G for thermal mass flowmeters on carrier gas (air) flowrates.
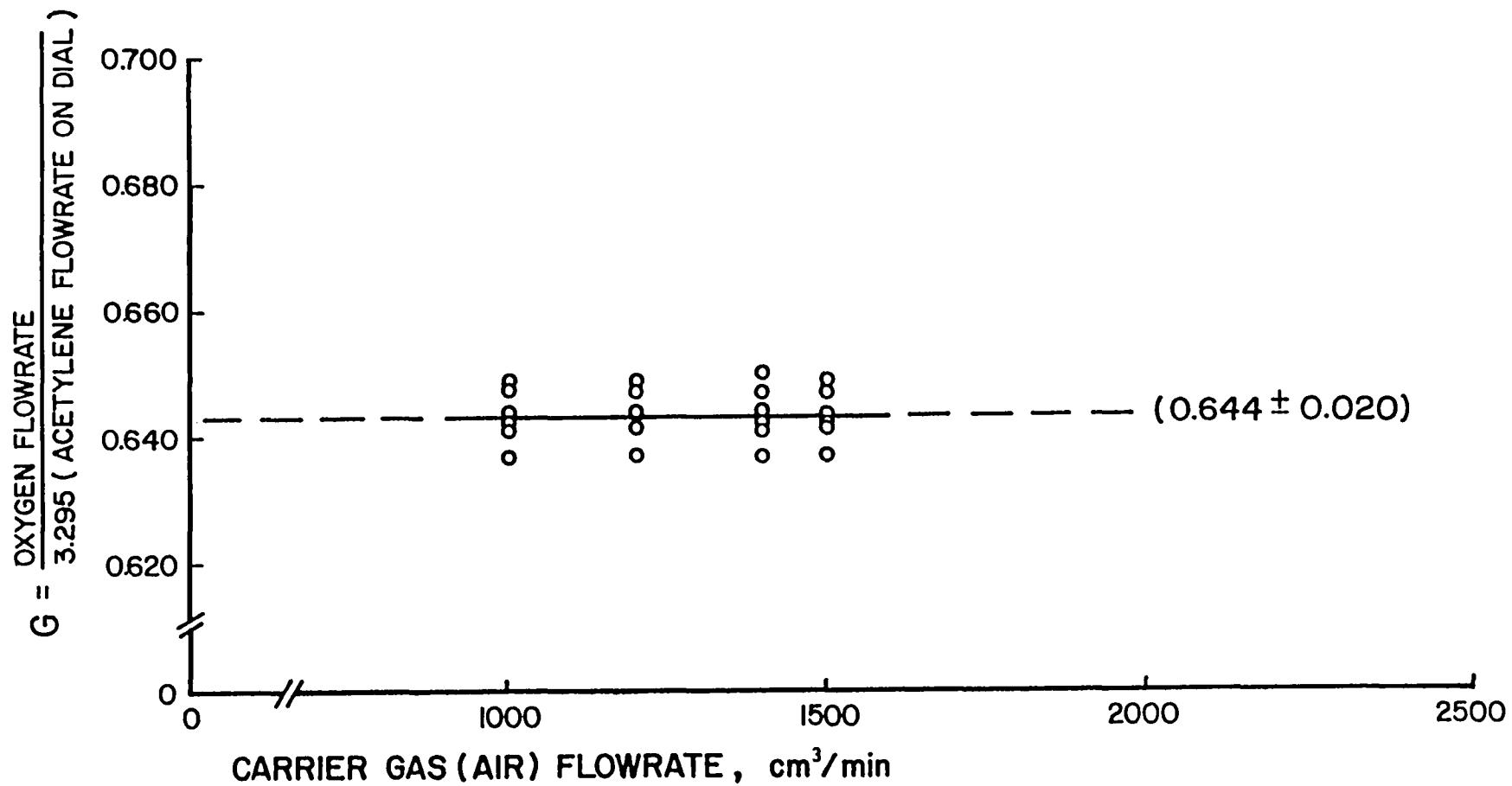
Figure 5.- Dependence of acetylene conversion factor G for thermal mass flowmeters on carrier gas (air) flowrates.
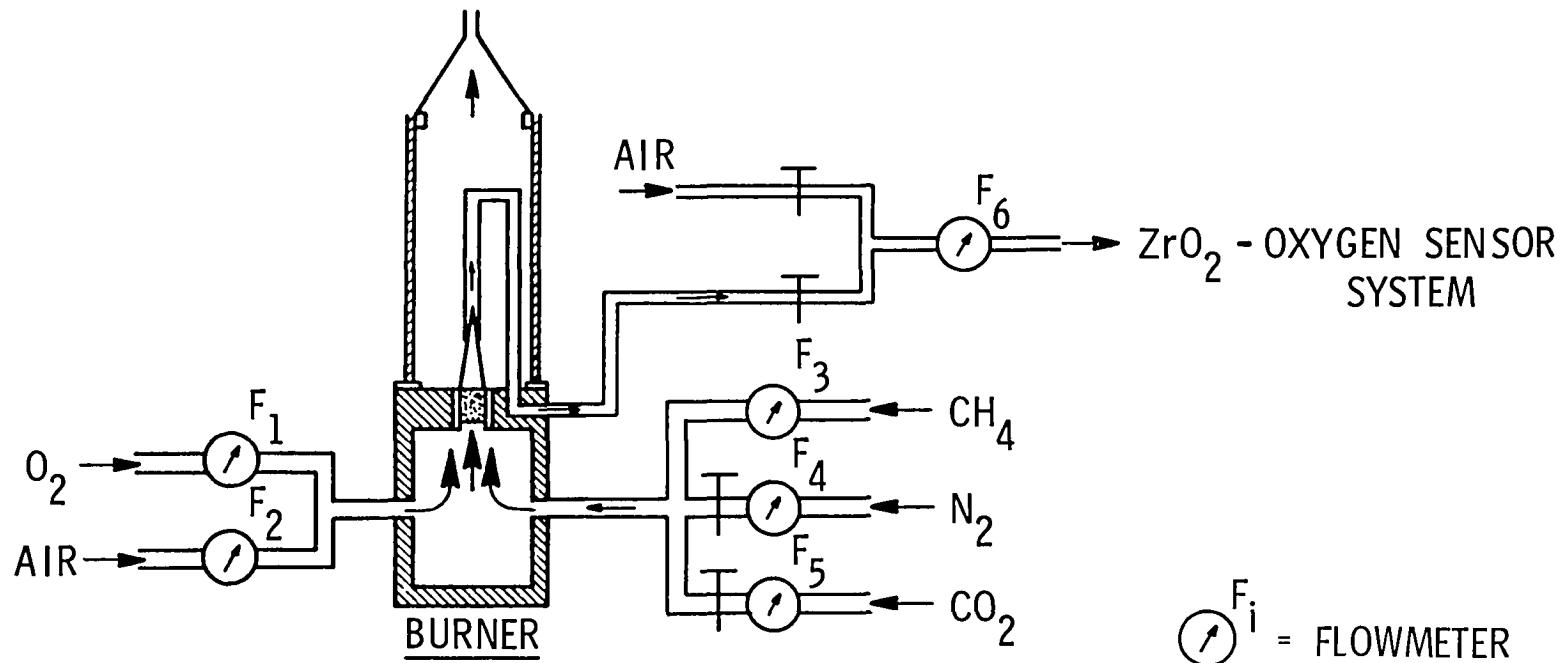
Figure 6.- Experimental system for measuring N_2 and CO_2 contaminant concentrations in CH_4 stream.
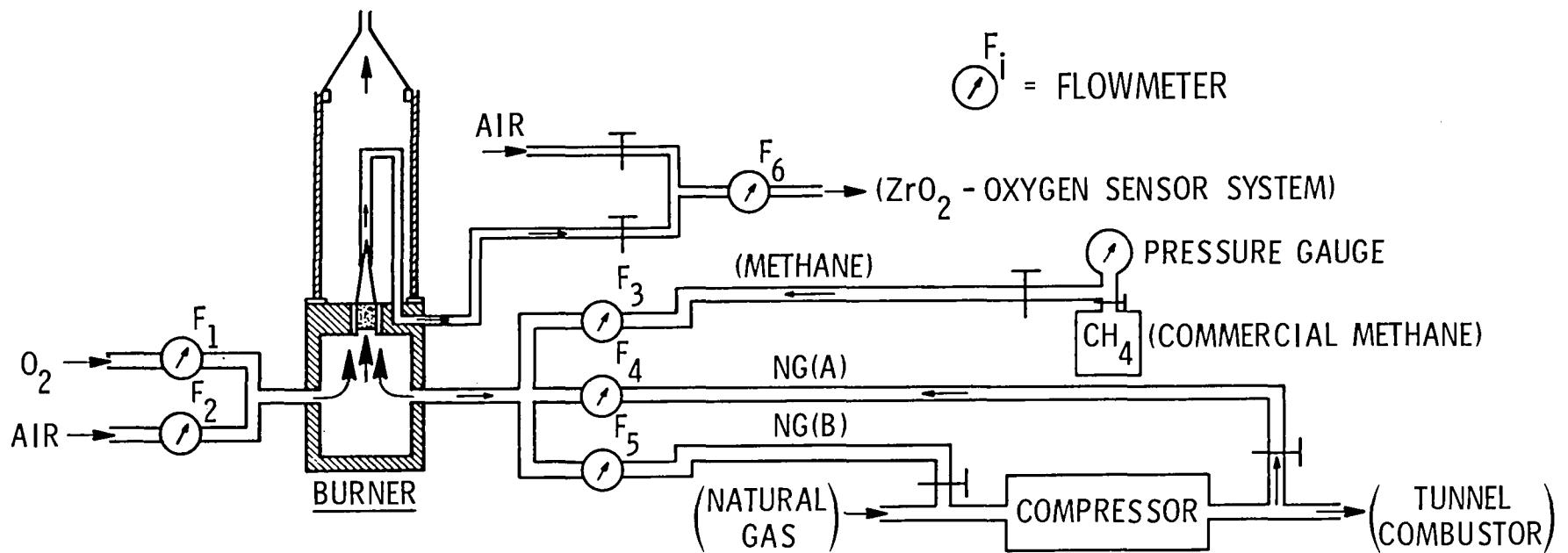
Figure 7.- Experimental system for monitoring quality of commercial natural gas.

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15. Supplementary Notes

16. Abstract

A new technique for measuring calibration correction factors for hydrocarbon mass flowmeters has been developed. It is based on Nernst theorem for matching the partial pressure of oxygen in the combustion products of the test hydrocarbon, burnt in oxygen-enriched air, with that in normal air. It has been applied to a widely used type of commercial thermal mass flowmeter for a number of hydrocarbons. The calibration correction factors measured using this technique are in good agreement with the values obtained by other independent procedures. The technique has been successfully applied to the measurement of differences as low as 1 percent of the effective hydrocarbon content of the natural-gas test samples.

17. Key Words (Suggested by Author(s)) Hydrocarbon flowmeter Thermal mass flowmeter conversion factor Oxygen partial-pressure monitor ZrO_2-oxygen sensor Natural gas quality factor	18. Distribution Statement Unclassified - Unlimited Subject Category 35

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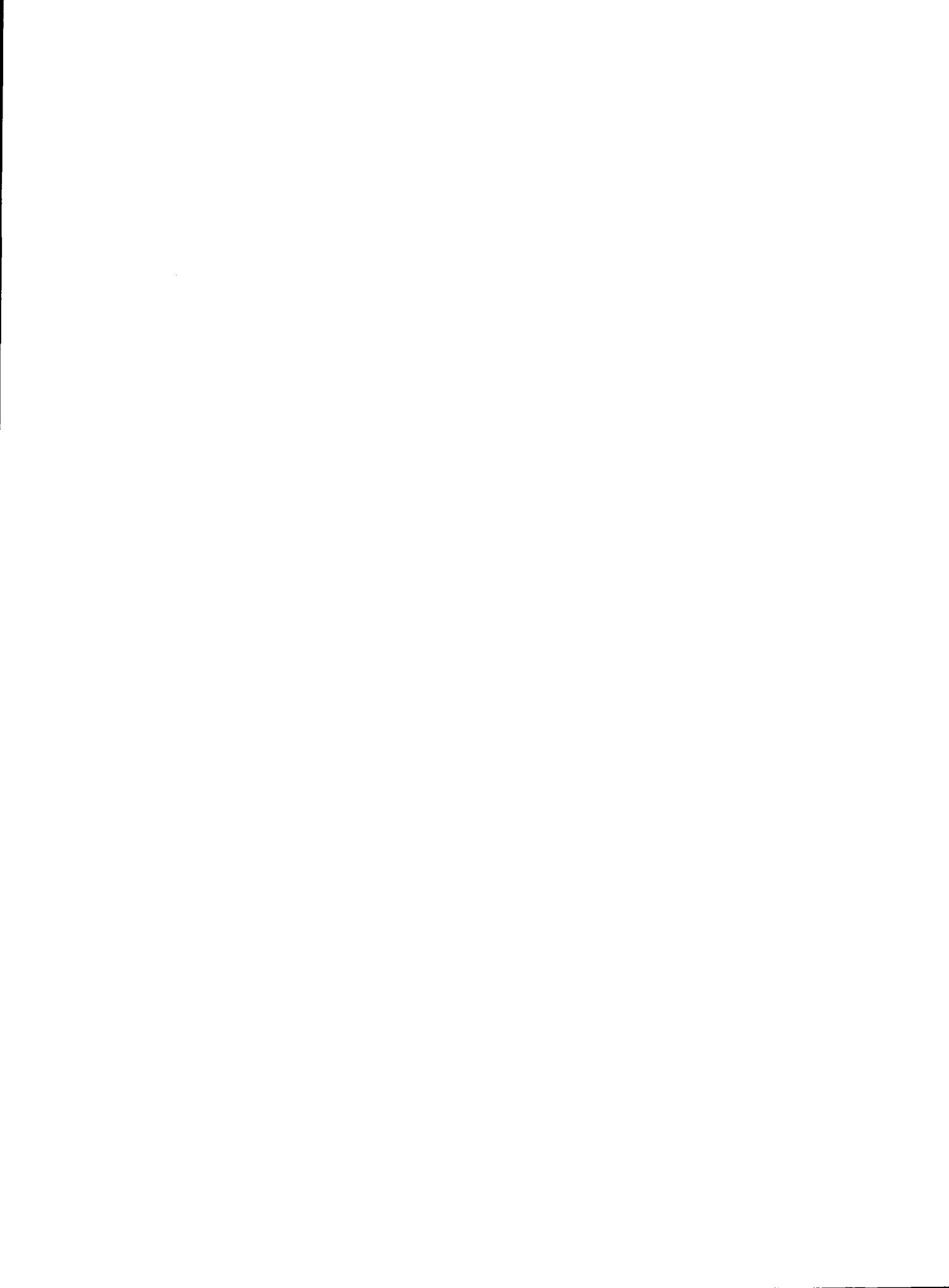
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